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Rotman Lens Antenna in Microstrip Configuration

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ABSTRACT

The area of microwave is very broad and it is now being developed to support wide band, wide angle and true time delay systems. Rotman lens antenna is a successful candidate in this developing area and is based on true time delay. The lens uses its beam ports to illuminate the array ports which in turn radiate the energy to the array of radiating elements. They provide ideal performance for applications such as for satellite based direct radiating, Radar based systems and many more.

The thesis will review, analyze and design a Rotman lens antenna using the Rotman lens design tool (RLD) tool and MATLAB. The aim of this research work is to optimize the performance of the Rotman lens in terms of minimizing the phase error and improving the scanning capabilities with low loss. The antenna should be capable of producing multiple beams which can be steered without changing the orientation of the antenna. The lens feeds a linear array of Microstrip patch antennas which acts as radiating elements. Various parameters optimized are phase error, scanning angle, side lobe level, radiation pattern and return loss.

Key words: Rotman lens antenna, RLD software, array factor, substrate, side lobe level, return loss, focal length, beam port, array port, dummy port.

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INTRODUCTION

Rotman lens are attractive candidates for use in beam forming networks (BFNs).These antennas are used in the radar surveillance systems to see targets in multiple directions due to its multi-beam capability without physically moving the antenna system. This lens is now integrated into many radars and Electronic Warfare systems around the world. This thesis will review, analyze and design a Rotman lens antenna using RLD tool. The aim of this research work is to optimize the performance of the Rotman lens in terms of minimizing the phase error and improving the scanning capabilities with low loss. The antenna should be capable of producing multiple beams which can be steered without changing the orientation of the antenna. The lens feeds a linear array of Microstrip patch antennas which acts as radiating elements. The frequency range for the design could be as low as 450MHz to mm waves **GA optimizing techniques** are applied on Rotman lens and Microstrip patch antennas to give the desired optimized results of phase error, scanning angle and return loss.

They provide ideal performance for applications such as for satellite based direct radiating, Radar based systems and many more.

LITERATURE REVIEW:

Research work on the Rotman lens antenna started way back in **1963** when **W.Rotman and R.F.Turner** published their research work.In this work basic design equations of Rotman lens were derived for improving scanning capability of the lens along with the reduction in beam to array port phase error. This work still remains the benchmark for researchers in this area.

In **1984 Takashi Katagi improvised** the design equations by **W.Rotman and R.F.Turner** by adding a new variable which reduced the phase error on the aperture of the linear array antenna. This design parameter helped in reducing the size of the lens.

In **1989 Smith et al.** presented with a new design approach for reduction of side wall absorption which is one of the performance limiting parameter of the lens.

A big breakthrough in this work came in **1991** when R.C.Hansen analyzed the effects of design parameters on shape, phase error and amplitude error of the lens.

In 1990 P.S. Hall et al. reviewed radio frequency beam forming techniques and presented a very wide range of solutions incorporating both quasi optics and circuit base type networks. They found that the reflectors and lenses produce high gain beams with very narrow scan ranges. Circuit beam formers have the well known traveling wave or corporate feed characteristics and can be used in limited size array as can the Rotman and Rize Lens which in addition gave wide bandwidth.

In 1992 R.C. Hansan proposed that the antenna array distribution and its associated patterns based on the array polynomial. The control of side lobe topology in pencil beam patterns, Dolph Chebyshev and tailor distributions and the synthesis of beam patterns were discussed. Finally the ultimate pencil beam array and the super directive array were evaluated.

In 1995 S.F. Peik et al. proposed a practical design for control of traffic lanes using multiple beam micro strip array fed by a Rotman lens. The traffic lane had been divided into five communication zones which had to be monitored independently.

In 1996 Ekkehart O. Rausch et al. proposed a design based on the contour integral. A mm wave Rotman Lens that operates between the freq. of 33-37 GHz. was designed. Various parameters were analyzed. Reduction in the side lobe level and insertion loss was observed .Greater scanning angles were possible with different lens design. **In the same year** – Multibeam Array using Rotman Lens and RF Heterodyne was proposed by JJ Lee. The RF heterodyne technique was applied to Rotman lens to reduce the size of the beam forming network for airborne antenna operating at L – band (1.4 GHz).

1996 – Low Cost Compact Electronically Scanned mm Wave Antenna was proposed by E.O. Rausch, Jay Sexton and Andrew F Peterson, good reduction in side lobe levels and insertion loss was achieved .

In **2003 Singhal et al.** proposed the fact that the height of the array and feed contours must be same for maximum power transfer and better lens performance .Effect on the shape of the beam and array contour by variation in scanning angle, focal ratio and element spacing were prime issues of his work.

Peter.S.Simon in **2004** analyzed the performance of the lens using his own simulation tool designed in MATLAB platform. It was probably the first reported GUI especially designed for Rotman lens antenna .Accuracy of author's proposed Rotman lens design software is verified by comparing its results with NARL (Numerical Analysis of Rotman lens).

In view of all the above mentioned facts by various researchers it is quiet clear that still there was a scope of improvement in the performance of the lens.

In **2007 Dirk Nubler** et.al.designed a Rotman lens for mm waves (94 GHz), this was a first approach for 2D lens stacking which solved the problem of beam shifts over a frequency range. The scanning angle could not exceed 20 degrees.

In **2009 R.Uyguroglu** et al. introduced a new concept of feed curves such that the phase error was reduced .The method was based on having three zero error positions on the radiating array for each feed curve point.

In **2009 J.Dong** et al. reported a design of a microwave lens which had the capability of 360 degree scanning .This has been a major breakthrough since a work of this kind was never reported where lens had achieved the capability of complete 360 degree scanning.

After **2009** various researchers are still trying to improve the design of the lens so as to achieve a wide angle scanning with low lens loss and minimum phase error .Use of various existing optimization techniques namely genetic algorithm, particle swarm optimization, simulated annealing etc. can come handy in improving the performance of the lens.

DESCRIPTION OF ROTMAN LENS ANTENNA

A Rotman lens is built using microstrip techniques, feeding a patch antenna array .It satisfies the qualities required in an antenna as it provides high gain, large scan angles, conformal geometry and low cost [32] [21] [37]. There is a lot of scope in optimizing various parameters which are useful in designing Rotman lens antenna [37]. The antenna is capable of producing multiple beams which can be optimized to steer without changing the antenna orientation [9] [37] . **Fig.1** [32] shows a basic diagram of the Rotman lens. It consists of a set of input and output ports arranged along an arc. The lens structure between both sets of ports functions as an ideal transmission line between the individual input and output ports. The signal applied to the input port is picked up by the output port.

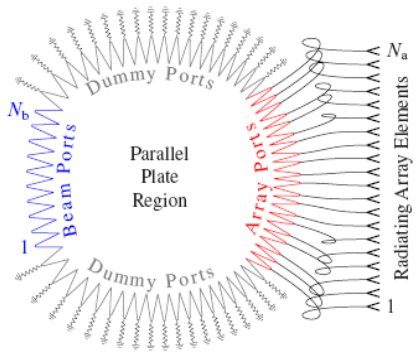

Fig 1.Basic construction of Rotman lens

The different electrical lengths between a specific input and all output ports, generates a linear progressive phase shift across the output ports of the lens. Dummy ports are also an integral part of the Rotman lens and serve as an absorber for the spillover of the lens and thus it reduces multiple reflections and standing waves which deteriorates the lens performance [16].The design of the lens is governed by the Rotman-Turner design [36] [38] equations that are based on the geometry of the lens as shown in **Fig.2**

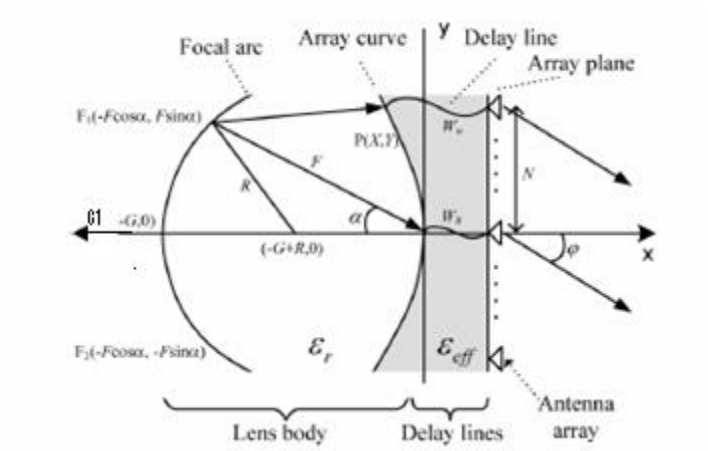

Fig 2. Geometry and design parameters of Rotman lens

Fig.2 shows a schematic diagram of a trifocal Rotman lens [14] [37]. Input ports lie on contour C_1 and the output ports lie on contour C_2. C_1 is known as beam contour and C_2 is known as array contour. There are three focal points namely F_1, F_2 and G_1. G_1 is located on the central axis while $F_1$and F_2 are symmetrically located on the array contour at an angle of $+\alpha$ and $-\alpha$ respectively [37] [39]. It is quite clear from **Fig.2** that the co-ordinates of two off-axis focal points F_1, F_2 and one on axis focal point G_1 are $(-F\cos\alpha, F\sin\alpha)$, $(-F\cos\alpha, -F\sin\alpha)$ and $(-G, 0)$ respectively. The equations generate the positions of the antenna ports based on three perfect focal points (G_1, F_1, and F_2) [37]. The defining parameters of the Rotman lens are the on axis and off axis focal lengths G_1, F_1 and F_2, internal scan angle α, focal ratio the number of beam and antenna ports and the external scan angle [13] [37] [38] [39] [40]. When a feed is placed at a non focal point then the corresponding wavefront will have a phase error [34], but for wide angle scanning capabilities it is necessary to place the feed at non focal points.

Design Equations of Rotman lens antenna

We have

G-On axis focal length

F-Off axis focal length

α -Off center focal angle

ψ_α -Scanning angle

$\gamma = \frac{\sin\psi}{\sin\alpha}$ - Beam angle to ray angle ratio given as ratio of sine of their angles.

ε_r -Permittivity of medium in between the lens contour

ε_e - Permittivity of medium of transmission line

ε_i -Permittivity of medium of radiating element

$g = \frac{G}{F}$ focal ratio

W_o- Transmission line length between axis point 'O'and radiating element.

W-Transmission line length between point 'P'and radiating element.

If we assume that the ideal focal points are located at $\theta = \pm \alpha$ and 0, and their corresponding radiation angles are $\Psi = \pm \Psi_\alpha$ and $\Psi = 0$, given Ψ_α is a known angle, simultaneous equations 1-3 are satisfied [35] [37] [40]:

$F_1 P + W + N\sin\alpha = F + W_0$ ----------(1)

$F_2 P + W - N\sin\alpha = F + W_0$ ----------(2)

$G_1 P + W = G + W_0$ ----------(3)

By algebraic manipulation of the above equations we can obtain geometric lens equation which is quadratic in nature and is given by-

$aW^2 + bW + c = 0$

Where-

$$a = \left[1 - \eta^2 - \frac{(g-1)^2}{(g-a_o)^2}\right]$$

$$b = \left[-2g + 2\eta^2 - \frac{b_o{}^2\eta^2(g-1)}{(g-a_o)^2} + \frac{2g(g-1)}{(g-a_o)}\right]$$

$$c = \left[\frac{g b_o{}^2\eta^2}{(g-a_o)} - \frac{b_o{}^4\eta^4}{4(g-a_o)} - \eta^2\right]$$

W -Normalized relative transmission line length

and is given as $W = (\frac{w - w_o}{f_1})$.

a_o=sinα and b_o=cosα

Limiting factors in the design of Rotman lens

i) Reflections from the Sidewalls: The reflections from the side walls of the array and the beam port are the factors which limits the performance of the lens.The side walls are designed in such a way that the reflected radiation within the lens is minimum.As there are two ports in the lens antenna i.e. array port and the beam port hence two sets of dummy ports are designed, one is to deal with the radiation from the antenna ports and the other to deal with the radiation from the beam ports [18]. **Fig.3** [18] shows the orientation for well designed sidewalls. Less energy from the antenna ports will be incident on the beam dummy ports and the energy that does, is reflected directly onto the antenna dummy ports.

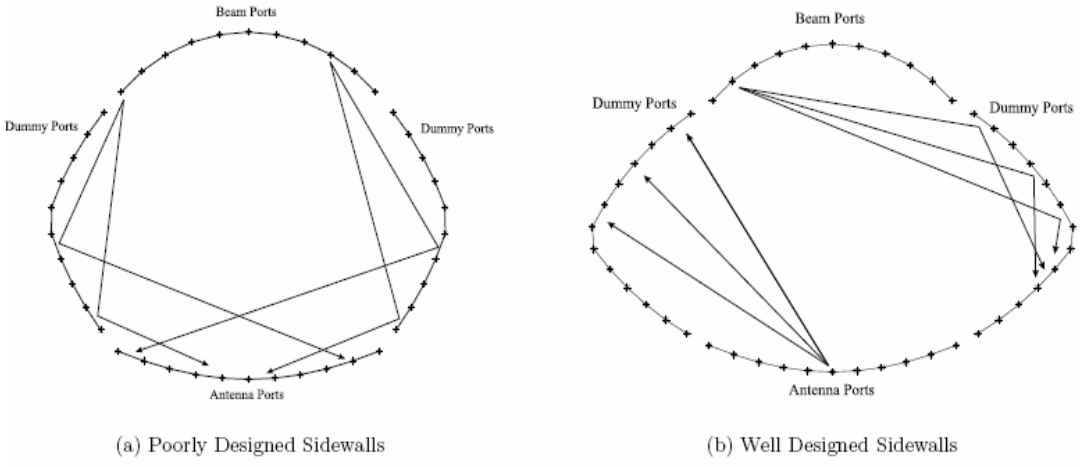

Fig.3.Side walls with dummy ports

ii) Grating lobes: Element spacing is also very critical as it controls the appearance of grating lobes.

iii) Array factor: Array factor is an important factor in the analysis of Rotman Lens performance. Array factor analysis can indicate the behavior of side lobe levels and the scanning directions [36].

iv) Phase error: Phase error is defined as the difference between the actually needed phase and the obtained phase. Optimization of phase error plays an important role. It can be achieved by various numerical analysis techniques available like Genetic algorithm, PSO (Particle swarm optimization) DSZ algorithm. I will be using GA for optimization.

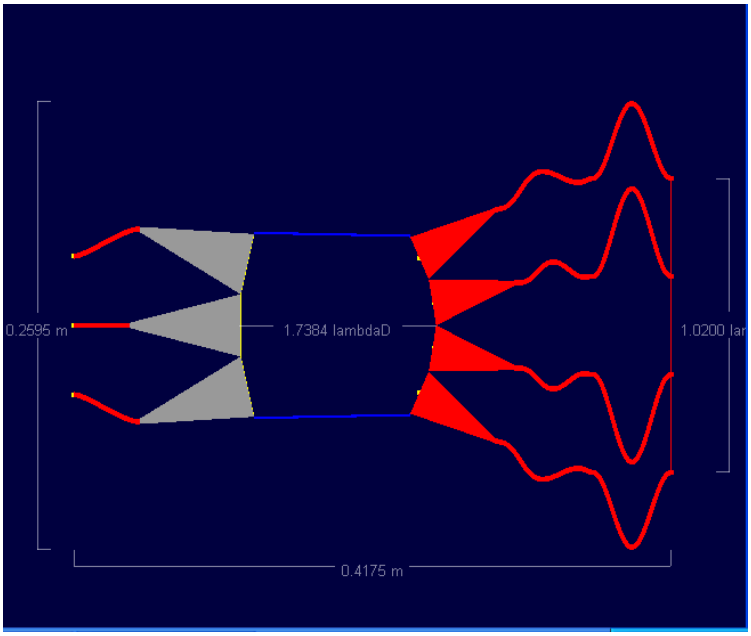

Fig.4 Design example of a Rotman lens antenna

The design example is shown in fig.4 [37] above which is designed using the following parameters [37] as given below:

Elliptical lens with the distance between the elements d =0.34λ

Operating frequency=1.8GHz

Scan angle=30degree

Alpha ratio=5

No. of beams=3

With Absorber side walls

Flare angle=12 degree

Focal length=1.7384 λ

Focal ratio g-varying

Description of Microstrip patch antenna as radiating elements:

In order to work with the small size electronic system, high performance antenna designs are the need of the time . Microstrip or patch antennas are becoming increasingly useful because they can be printed directly onto a circuit board[3][21][22]. Patch antennas are low cost, have a low profile and are easily fabricated. The design of high performance microstrip antenna has always been a challenge for the antenna designers. This is due to the fact that patch antennas have narrow impedance width and at times the requirements of a particular application can be very hard. Consider the microstrip antenna shown in **Fig. 5**, fed by a microstrip transmission line [3]. The patch antenna, microstrip transmission line and ground plane are made of high conductivity metal (typically copper). The patch is of length L, width W with a substrate of thickness h and permittivity ε_r [3].

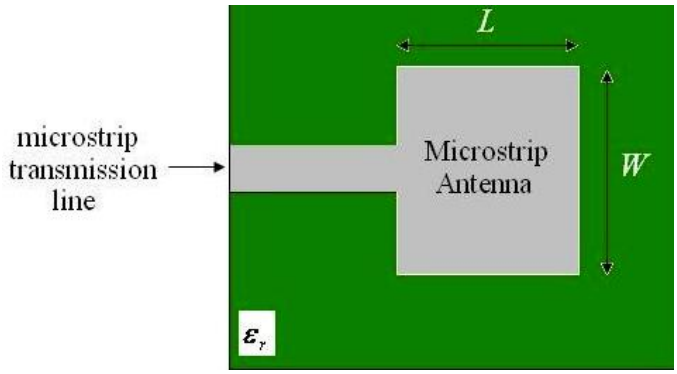

Fig.5.Microstrip patch antenna

Microstrip antennas have the main limitations in terms of bandwidth, poor polarization purity, limited power capacity and efficiency; all imposed by the presence of dielectric substrate [22]. The radiating patch may be square, rectangular, triangular or any other

configuration. Square microstrip antennas have a big advantage due to their polarization diversity particularly its ability to realize dual or circularly polarized radiation patterns. In order to overcome the shortcomings of the patch antenna it is important to make an optimal antenna design for best performance [3] [7]. Various existing optimization algorithms can come handy in this case and genetic algorithm which is one of the global optimization algorithms will be used for optimization of the patch shape in order to achieve better overall performance of the antenna.

There are various parameters which will be analyzed for Rotman lens and MPA (Microstrip patch antenna)

Parameters of Rotman lens are :

- Phase error
- Array factor
- Maximum scanning angle
- Beam to array port phase error
- Insertion loss
- Beam to side wall coupling
- S-parameters

Parameters for MPA are:

- Return loss
- VSWR
- Antenna Efficiency
- Gain
- Radiation pattern
- Directivity
- Polar plot
- Impedance

OBJECTIVES OF THE STUDY:

Due to the rapid advancement in wireless communication system, the need for efficient antenna design with good radiation capability, multiple simultaneous beams and with the small size is imperative. Research work to improve the antenna design for obtaining desired goals has been carried out by various researchers in the last few decades. Smart antennas with wide scanning angle capabilities have resulted out of continuous efforts in making an efficient antenna design. Modern day cutting edge applications like Radar and satellite communication require antennas with wide scanning angle capabilities and good performance over a broad frequency range. Antennas used in various applications should satisfy some common criteria i.e. small size, light weight and good radiation properties. These requirements are best suited by MPA (Microstrip Patch Antenna). Antenna array is employed where we want to achieve some properties which might not be possible by a single MPA. Different configurations of the antenna array have been reported by various researchers in the recent past like linear array, planar array, 3D array etc. Different types of feeding techniques can be used with these configurations for example Series feed, Corporate feed etc. each having its merits and demerits .The design of an MPA is an important aspect for achieving optimal performance of the overall array.

Rotman lens named after W. Rotman has emerged as one of the best structures that can be employed for achieving wide angle scanning capabilities. They are used in beam forming networks and have been used in Radar applications for the detection of an approaching target. Previous work carried out on Rotman has been mostly based upon integration of Rotman lens with MPA array for achieving wide angle scanning, but the performance of the system is limited due to inefficient lens design. Phase error is one of the most important parameters that limits the performance of Rotman lens antenna [37].

In view of all the above mentioned facts the effect of change of shape of the beam port, array port and the change of substrates with different dielectric constants affects various parameters of the lens and eventually the performance of the lens. It is quite evident that for achieving minimum phase error wide scanning capability Rotman lens design needs to be optimized along with the optimization of MPA (Microstrip Patch Antenna) array using optimizing techniques.

METHODOLOGY

Software tools used: Various commercial software packages are available for simulating the behavior of an MPA (Microstrip Patch Antenna) and its array. The most popular amongst them are IE3D, CST microwave studio and HFSS. For designing the Rotman lens, Rotman lens designer (RLD) tool from REMCOM Corporation can be used. XFDTD tool from REMCOM Corporation can be used along with RLD for producing a Gerber file which is required for the fabrication of the Rotman lens antenna. **In my work I'll be using IE3D software for analyzing the performance of MPA and its array along with tools from REMCOM Corporation for Rotman lens design**. For optimization of MPA **genetic algorithm optimization** technique will be employed. IE3D has inbuilt EM optimizer which can be used in situations where manual tuning is not possible to achieve the desired performance goals. Problem of phase error optimization in the Rotman lens will also be catered by genetic algorithm optimization technique.

Antenna design involves various complex calculations which might be time consuming if done manually hence **MATLAB tool** will be used for reducing manual effort and design time. **MATLAB GUI** will be created for obtaining patch dimensions for different feeding arrangements and shapes. Array factor and radiation pattern plots for different array configurations will also be included in the **MATLAB GUI**.

PROPOSED OUTPUT OF THE RESEARCH

My work will aim at designing the Rotman lens for wide angle scanning and low phase error by utilizing the capabilities of **Genetic algorithm optimization**. The Genetic algorithm optimization tool has been used to optimize an edge fed rectangular microstrip patch antenna which acts as radiating elements. It helps to calculate various dimensions like length, width, position of the feed probe etc. for an MPA (Microstrip patch antenna) faster and efficiently. The MATLAB GUI has been created for various parameters of Rotman lens and MPA (Microstrip patch antenna).

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